

Estimating the Rate of Technology Adoption for Cockpit Weather Information Systems

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ABSTRACT

This paper summarizes the results of a survey to estimate the market penetration rate of cockpit weather information systems in five aviation markets: transport, commuter, general aviation, business, and rotorcraft. It begins by describing the general features that survey respondents identified as necessary characteristics for the market success of cockpit weather systems. Next the paper analyzes the financial benefit of cockpit weather systems for each market segment. Decision reversal tables and Monte Carlo simulation are employed to examine the sensitivity of the financial results to changes in the cost and savings elements. Finally, estimates for adoption rates in the five aviation market segments are presented.

INTRODUCTION

In February 1997, President Clinton established a national goal to reduce the fatal accident rate for aviation by 80% in ten years. As a part of the overall NASA response to this initiative, the Aviation Safety Program was created to achieve a reduction in the aircraft accident rate by a factor of five in ten years and by a factor of ten in twenty years. Weather oriented research is a key element in achieving these objectives since weather related accidents comprise 33% of commercial carrier accidents and 27% of General Aviation (GA) accidents. The availability of timely and accurate weather information for pilots is believed to be a key element in reducing weather related accidents [1].

Within the Aviation Safety program, the Aviation Weather Information (AWIN) project was created with the goal of developing the technologies that will provide accurate, timely, and intuitive information to pilots, dispatchers, and air traffic controllers to enable the detection and avoidance of atmospheric hazards. Currently, in-flight weather information is available primarily through the specific request of the flight crew using voice, radio, or data links. AWIN endeavors to broaden these weather tools and provide more advanced cockpit weather systems that allow pilots to know what kind of weather

they are approaching and to evaluate and select a safe course of action when confronted with adverse weather.

AWIN efforts have included a focus on understanding user-centered requirements for weather products, systems, and components. An element of this effort is to assess existing and under-development weather information technologies and concepts. This paper presents results of a survey that was developed and administered as a part of these AWIN activities. Specifically, this study examines critical questions related to adoption of cockpit-based weather information systems:

- What are the general product characteristics of the cockpit weather systems that eventually will achieve success in the target markets?
- What is the financial motivation (business case) for adoption of advanced cockpit weather systems by these market segments?
- How quickly will the market segments adopt cockpit weather systems?

The AWIN project team will use this information, along with other aviation data, to support NASA efforts in meeting President Clinton's goal for enhanced aviation safety.

SURVEY AND PARTICIPANT DESCRIPTION

The survey was developed and administered by the Department of Engineering Management at Old Dominion University for the AWIN project at the NASA Langley Research Center. The primary survey objective was to obtain industry estimates for the rate at which advanced cockpit weather systems will penetrate five important market segments: transport, commuter, general aviation, business, and rotorcraft. Secondary goals included definition of the general characteristics of successful advanced cockpit weather systems, both operational and financial, and the reasons for adoption of these systems.

A user survey questionnaire was developed and distributed to 60 organizations selected to represent the primary groups involved in the aviation market. The

survey contained 27 questions and included the opportunity for open-ended comments from participants. The complete survey is contained in Appendix A. It was developed using a collaborative process involving NASA researchers, industry representatives, and trade group participation. The survey was formulated to obtain general market information that could direct future, more specific and detailed data gathering efforts. To use participant time as efficiently as possible, the survey was structured to require less than one hour to complete.

Survey participants included weather information providers, data and communication link providers, avionics companies, airframe manufacturers, and industry/government / trade groups. Key decision-makers within the selected organizations were identified to receive the survey. Participants were screened to assure that they possessed a broad view of the weather information market coupled with significant responsibilities in cockpit weather related activities and products. Participants were instructed to respond to market segment questions only within their areas of expertise. In many cases, respondents were involved in several market segments. As a result, the sample size is typically in excess of twenty for each response category. The survey instrument was completed and distributed in October 1999. Completed surveys from 32 organizations were returned between November 1999 and February 2000.

GENERAL DESCRIPTION OF SUCCESSFUL COCKPIT WEATHER INFORMATION SYSTEM

The first group of survey questions asked the participants to describe their views on the characteristics of the cockpit weather systems that will eventually achieve market success. This section describes those responses.

GENERAL SYSTEM DESCRIPTION

The first question asked whether the participants agreed that the successful weather system would combine both graphical and textual weather information with a moving map geographical positioning system (GPS). Figure 1 shows that over 90% of the participants agreed or strongly agreed that this combination is a product success factor for all market segments.

RELATIVE IMPORTANCE OF WEATHER DATA TYPES

A wide range of weather data is available for use by the cockpit system. This question asked the participants to use a 1-5 scale (with 5 as most important) to rate the importance of six different categories of weather information: turbulence/shear, winds-aloft and surface, icing, moisture/precipitation, thunderstorm/convection, and visibility/ceiling. Figure 2 summarizes the results.

In general, participants rated winds and moisture/precipitation as less important weather information. Market segment differences are evident in selection of

the most important weather information. For example, the transport market identified turbulence/shear as most important while the commuter market considered thunderstorm/convection as most important. Icing and visibility/ceiling were also particularly important to the commuter segment. General aviation considered thunderstorm/convection and turbulence/shear as the most important weather data. For rotorcraft, visibility/ceiling was most important.

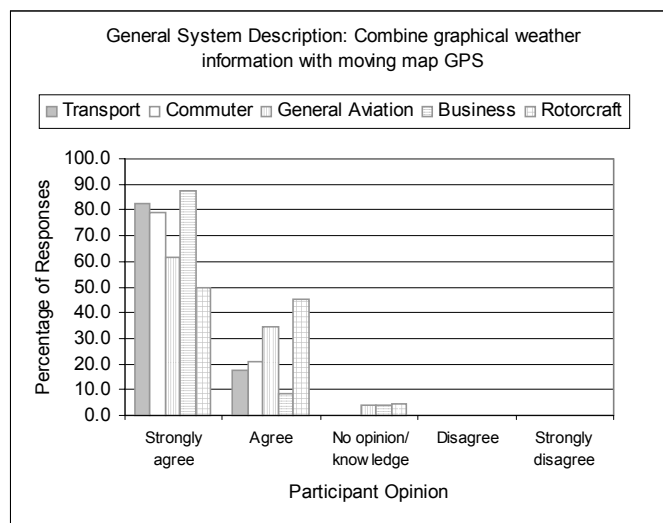


Figure 1 General System Description: Moving Map / GPS

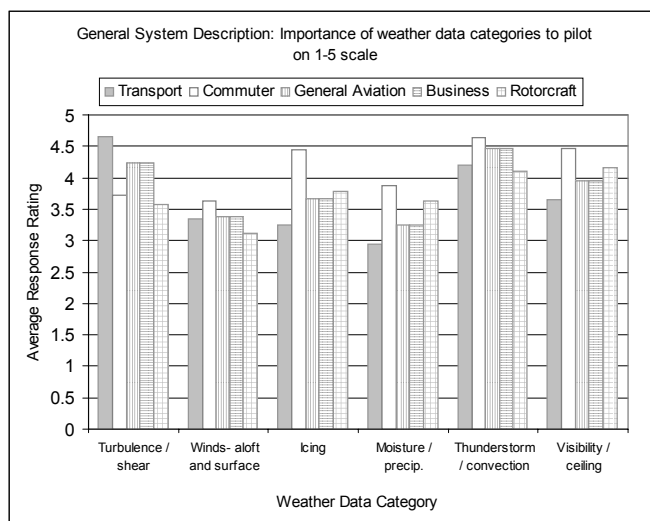


Figure 2 Importance of Weather Categories

IMPORTANCE OF WEATHER INFORMATION DURING FLIGHT PHASES

This question examined the participant's views of the flight phases during which cockpit weather information is most important and Figure 3 summarizes the results. Participants consistently rated cockpit weather information as most important during en route and approach flight phases for all market segments. Ground operations and departure were rated less important for all market segments.

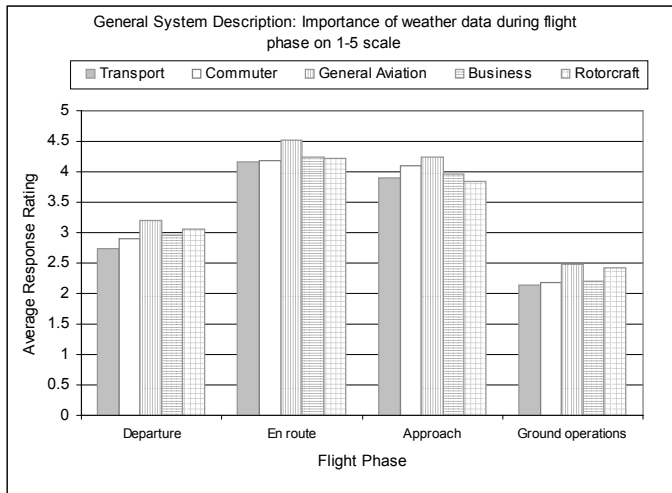


Figure 3 Importance of Weather Data during Flight Phases

STRATEGIC WEATHER INFORMATION

Strategic weather information enables early hazard detection and pro-active avoidance measures. This question examined the timeframe along the flight path strategic weather information should cover and whether differences in this view exist between the market segments. Figure 4 summarizes these responses. Over 50% of the rotorcraft responses required strategic weather information less than one hour ahead along the flight path. About 25% of the commuter and general aviation responses indicated that the strategic weather data requirement is also one hour or less. Over 50% of the commuter and about 40 % of the general aviation and business segments indicated that the strategic weather data requirement was between one and two hours. Nearly 50 % of the transport market and over 40% of the business market believed strategic weather information should cover more than two hours ahead.

STRATEGIC WEATHER INFORMATION UPDATE FREQUENCY

The frequency with which weather information must be updated can influence system components and design trade off decisions. This question asked participants to indicate the update frequency for strategic weather information that each market segment will require. Figure 5 summarizes the responses and indicates that the most frequently selected data update interval for all

market segments was 10-14 minutes. Approximately 40% of the transport, commuter and business respondents and 30% of the general aviation and rotorcraft respondents indicated a preference for the 10-14 minute update interval. Significant portions of each market segment also selected the 5-9 and 15-20 minute intervals.

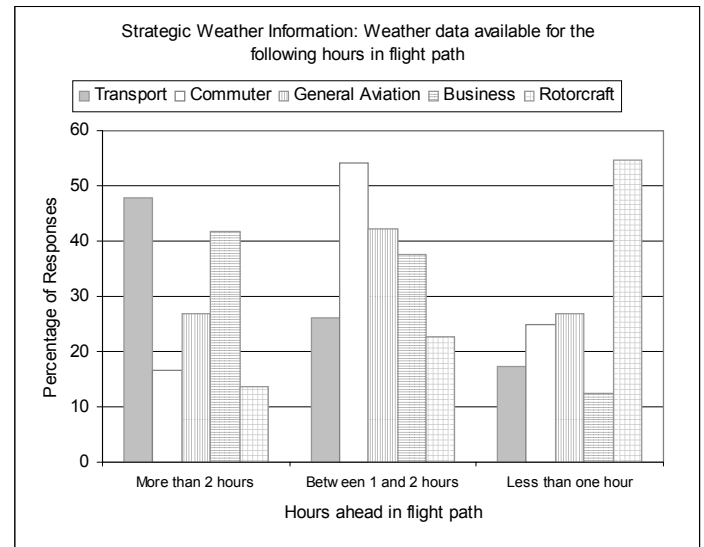


Figure 4 Weather Data Availability in Flight Path

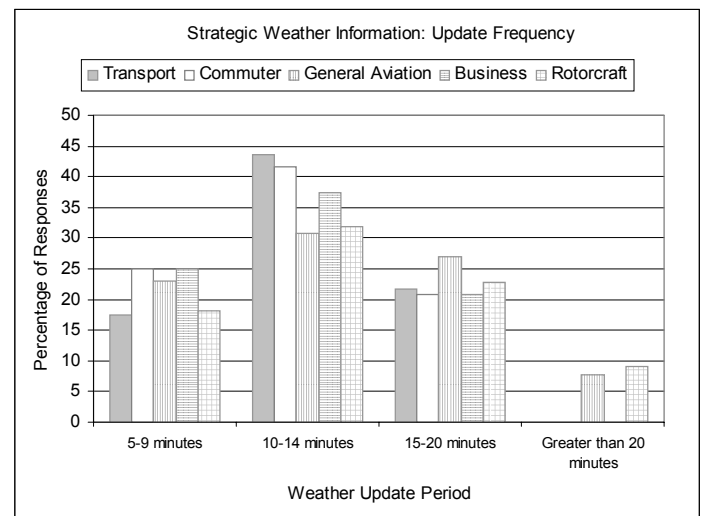


Figure 5 Strategic Weather Information Update Frequency

IMPORTANCE OF HISTORICAL AND FORECAST WEATHER DATA

This question examined whether the successful cockpit weather system should have the capability to present both historical and forecasted weather patterns. This combination of information may allow pilots to evaluate weather trends. Figure 6 shows that nearly 20-30% of responses in all segments indicated that only forecasted information is necessary for a successful cockpit weather

information system. On the other hand, 60-70% of all market segments indicated that market success would require both historical and forecasted weather data.

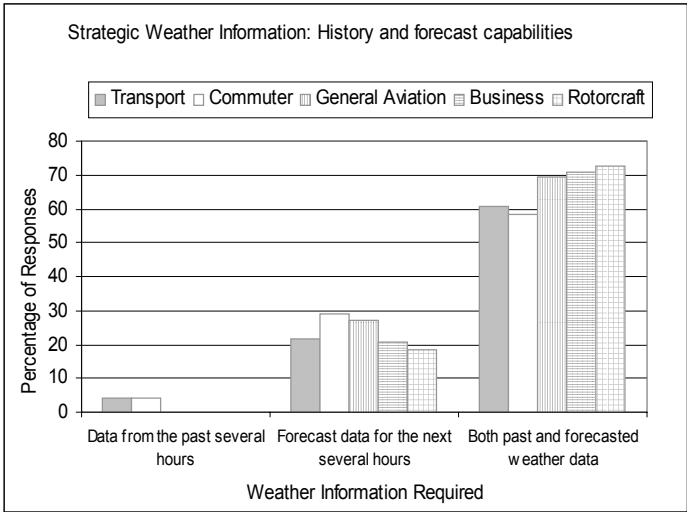


Figure 6 Strategic Weather Data: Historical and Forecast Capability

IMPORTANCE OF TACTICAL WEATHER INFORMATION DURING FLIGHT PHASES

Tactical weather information impacts cockpit decisions required to address immediate hazards. This question asked participants to use a 1-5 scale to rate the importance of tactical weather information during flight phases and Figure 7 summarizes the responses. In general, en route, descent, and approach are the most important flight phases for tactical cockpit weather information for all market segments. Departure and climb were rated as less important for most segments. For the transport and rotorcraft markets, the en route phase was rated as most important for tactical weather data. The general aviation market rated descent and en route as most important flight phases for tactical weather information.

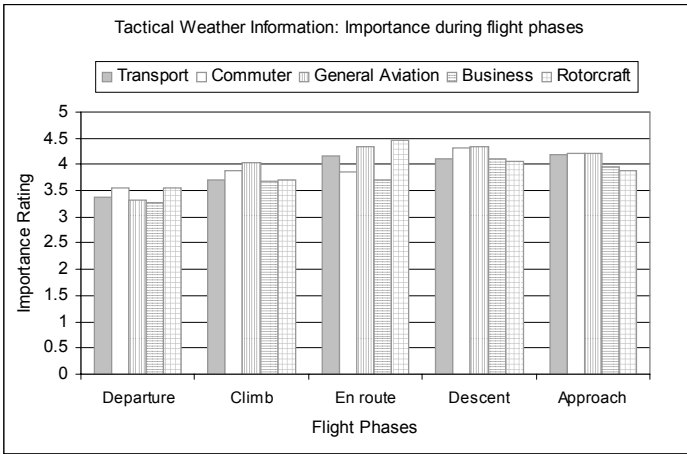


Figure 7 Importance of Tactical Weather Data during Flight Phases

IMPORTANCE OF BOTH STRATEGIC AND TACTICAL WEATHER INFORMATION

Although presentation of both strategic and tactical weather information in the cockpit is possible, it is not clear that this is necessary for market success. This question asked participants to evaluate the importance for market success that the advanced cockpit weather information system provide both strategic and tactical weather information. As Figure 8 shows, in excess of 75% of responses for all market segments agreed or strongly agreed that both strategic and tactical information should be provided for market success.

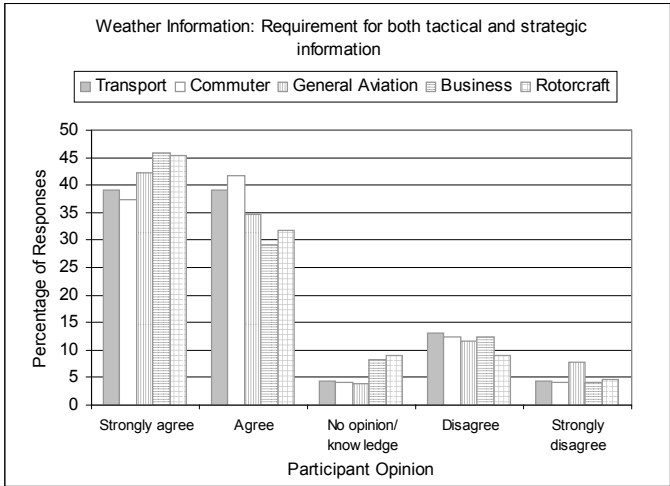


Figure 8 Tactical and Strategic Weather Information Requirement

DATA LINK SYSTEM

This question asked survey respondents to identify the data link system that will be successful in providing cockpit weather data for each market segment. Figure 9 shows that ground based VHF was the system selected for all market segments. The strongest preference for VHF was in the commuter and general aviation market segments. However, for most segments, the combination of satellite categories (LEO/MEO and geo-synchronous) exceeded the VHF preference. The transport segment demonstrates this point since over 30% indicated VHF would be the successful link approach but nearly 50% selected one of the satellite data links. Other significant satellite choices include over 25% of the transport and rotorcraft segments preferring geo-synchronous satellite and over 25% of general aviation selecting LEO/MEO.

DISPLAY HARDWARE DESCRIPTION

This question examined the cockpit display system that would be used by the successful weather system in each market segment. As Figure 10 shows, over 80% of the transport market and nearly 60% of the commuter and business responses indicated the display system should be integrated into current cockpit display systems. Nearly 40% of the rotorcraft and nearly 30% of the

general aviation responses indicated that a separate, stand-alone, display will be used. Also, about 30% of the general aviation responses indicate that the weather system display will be portable/removable.

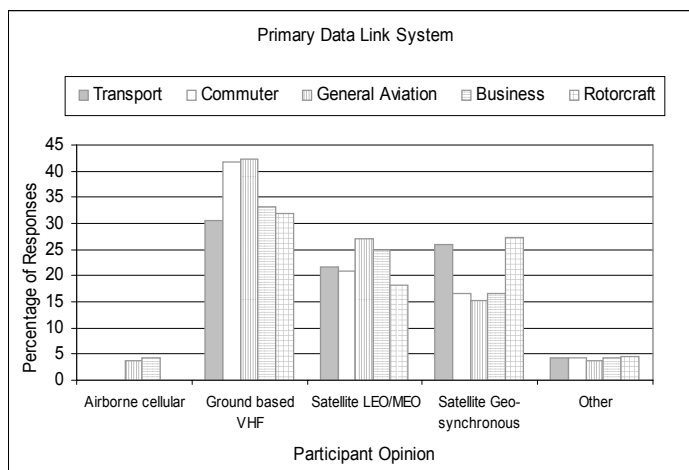


Figure 9 Primary Data Link System

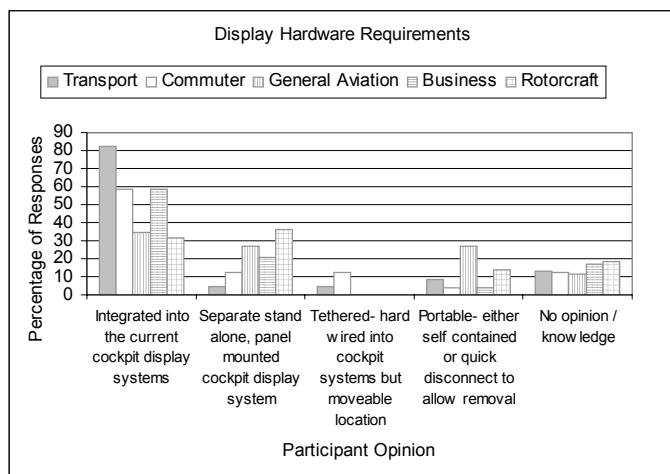


Figure 10 Display Hardware Requirements

PRIMARY REASON TO PURCHASE COCKPIT WEATHER SYSTEM

This question examined the motivations for the different market segments to purchase advanced cockpit weather systems. Figure 11 shows that survey participants believe the primary reasons to purchase will be cost savings and safety for most of the market segments. Nearly 60% of the commuter market responses indicate that cost saving will be the primary motivation for cockpit weather systems adoption. The transport market responses were split with about 40% indicating safety and a similar number indicating cost savings as the primary adoption factor. For the general aviation market however, nearly 70% believe that safety will be the dominant factor in the adoption decision. Over 20% of the transport segment responses and 15% of the business responses believe that packaging with other desirable systems will be the primary adoption reason.

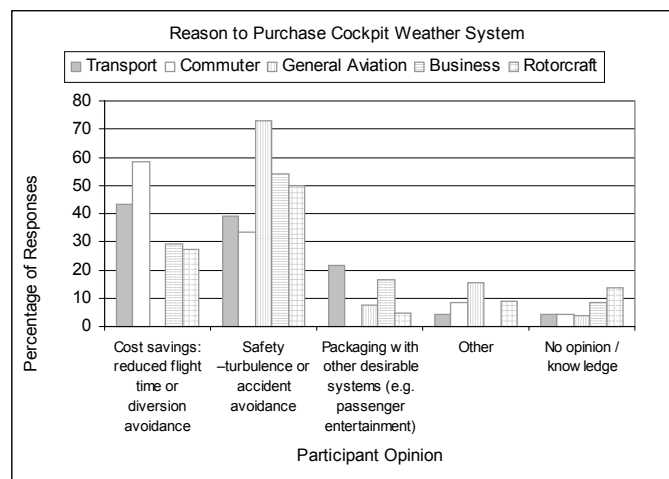


Figure 11 Reason to Purchase Cockpit Weather System

BUSINESS CASE FOR COCKPIT WEATHER SYSTEMS

The second section of the survey examined the financial costs and benefits of cockpit weather information systems. The survey asked for cost estimates associated with installation and operation of an advanced cockpit weather system in three categories:

- Recurring annual cost for the weather information and transmission to the cockpit.
- Non-recurring cost of the data transmission/link hardware that must be installed on the aircraft.
- Non-recurring cost of the display hardware that will be required by the weather information system.

Another group of questions examined the savings produced by installation and use of the cockpit weather systems. Survey participants were asked to estimate savings in three areas related to this new technology.

- Projected annual savings related to diversion avoidance by use of cockpit weather information.
- Minutes per month of flying time that will be saved by use of cockpit weather systems to select routes that will be more time efficient.
- Operating cost for a minute of flying time in the five market segments.

Together, responses to these questions can be used to evaluate the financial implications of investments in cockpit weather systems. The next section describes how the responses were analyzed.

ANALYSIS METHOD FOR GROUPED DATA

This section describes how the responses for the business case questions were organized in grouped data intervals and analyzed. Additional details on these methods can be found in statistical texts such as [2]. For a question with m response intervals ($i = 1, 2, 3, \dots, m$), each with a midpoint (M_i), the expected value (or mean response) for a market segment, \bar{x} , was calculated using Equation (1), where $p(M_i)$ is the probability of selection of interval (i) by a survey participant.

$$\bar{x} = \sum_{i=1}^m (M_i) p(M_i) \quad \text{Equation 1}$$

Similarly the response variance (S^2) was calculated using Equation (2) where f_i is the count in interval (i) and n is the total number of responses. The standard deviation (S) was calculated using Equation (3).

$$S^2 = \frac{\sum_{i=1}^m f_i (M_i - \bar{x})^2}{n-1} \quad \text{Equation 2}$$

$$S = \sqrt{S^2} \quad \text{Equation 3}$$

To compare the relative variation of the responses between the market segments, the coefficient of variation (CV) was calculated using Equation (4). The CV is the ratio of the standard deviation to the mean and provides a comparative measure of response variation. For example in a given question, the CV indicates whether the transport market response is more variable than the response from the commuter market. A larger CV indicates more variation in the responses.

$$CV = \frac{S}{\bar{x}} \quad \text{Equation 4}$$

RECURRING COST OF WEATHER INFORMATION AND DATA TRANSMISSION

This survey question asked participants to estimate the annual recurring costs that users of the successful advanced cockpit weather information systems in each market segment will incur to obtain weather information and have that data transmitted to the cockpit. Table 1 summarizes the responses. The CV values indicate that variability existed across all market segments but commuter responses were more variable than the other market segments.

Table 1 Recurring Annual Cost of Weather Information and Transmission

Question 11: Recurring Annual Cost of Weather Information / Transmission (\$)					
	Transport	Commuter	GA	Business	Rotorcraft
Expected value	5197	2045	433	1976	553
Standard deviation	4024	1840	316	1483	361
CV	0.774	0.899	0.729	0.750	0.653

NON RECURRING COST OF DATA TRANSMISSION HARDWARE

It is anticipated that cockpit weather systems will require purchase and installation of data and communication related equipment. This question asked survey participants to estimate the non-recurring cost of the data transmission/link hardware that will be acceptable by each market segment. Table 2 summarizes the results.

Table 2 Non Recurring Cost of Data Transmission / Link Hardware

Question 12: Non Recurring Cost of Data Transmission / Link Hardware (\$)					
	Transport	Commuter	GA	Business	Rotorcraft
Expected value	31579	12727	2100	15000	2789
Standard deviation	22672	8125	1275	9759	1575
CV	0.718	0.638	0.607	0.651	0.565

NON RECURRING COST OF DISPLAY HARDWARE

Adoption of advanced cockpit weather systems may require non-recurring investment in display hardware. This question asked survey participants to estimate the cost of the display hardware that users of the successful advanced cockpit weather information systems will accept in each market segment. Table 3 summarizes the results.

Table 3 Non Recurring Cost of Display Hardware

Question 13: Non Recurring Cost of Display Hardware (\$)					
	Transport	Commuter	GA	Business	Rotorcraft
Expected value	35833	16310	3792	18452	4833
Standard deviation	13504	10235	2629	9601	3125
CV	0.377	0.628	0.693	0.520	0.647

COST SAVINGS RELATED TO DIVERSION AVOIDANCE

Cockpit weather systems may enable decisions that avoid diversions and related costs. This question asked participants to estimate these annual savings and Table 4 describes the results. The transport and commuter segments had the highest annual cost avoidance savings followed by the business sector. Both the rotorcraft and general aviation markets had relatively higher variance in their responses as evidenced by the coefficient of variation.

Table 4 Annual Savings from Diversion Avoidance

Question 15: Annual Savings from Diversion Avoidance (\$/ yr.)					
	Transport	Commuter	GA	Business	Rotorcraft
Expected value	75000	25000	1000	17308	2083
Standard deviation	35843	12649	1000	8321	2285
CV	0.478	0.506	1.000	0.481	1.097

MINUTES OF FLIGHT TIME SAVED PER MONTH

This question estimated the monthly minutes of flight time that may be saved due to improved cockpit weather information systems. Table 5 summarizes the responses. When calculating the business case, these values are annualized and multiplied by the cost of a minute of flight time to obtain an estimate for flight time cost savings.

Table 5 Minutes per Month of Flight Time Savings

Question 16: Minutes per Month of Flight Time Savings (min. / mo.)					
	Transport	Commuter	GA	Business	Rotorcraft
Expected value	56	47	27	47	30
Standard deviation	36	33	19	30	20
CV	0.647	0.707	0.723	0.639	0.679

ESTIMATED COST OF FLIGHT TIME

This question estimated the average value of a minute of flight time for the five market segments. Table 6 summarizes the results. General aviation responses were the most variable.

Table 6 Estimated Cost of Flight Time

Question 17: Cost of a Minute of Flight Time (\$/min.)					
	Transport	Commuter	GA	Business	Rotorcraft
Expected value	74	33	2	33	5
Standard deviation	36	17	2	15	2
CV	0.484	0.533	0.686	0.450	0.447

EVALUATION OF COCKPIT WEATHER SYSTEM BUSINESS CASE

Responses to these cost and saving related survey questions provide information to develop a business case for adoption of the advanced cockpit weather information system. Using the expected values of the survey responses in Table 1 through Table 6 with Equation (5) below, it is possible to estimate the net present value (NPV) and internal rate of return (IRR) for an investment in advanced cockpit weather information systems. The IRR is the rate of return that results in a net present value of zero in Equation (5).

$$\text{NPV (cockpit weather system)} = -\text{Expected value (Non Recurring Costs)} - \text{PV [Expected value (Recurring Costs)]} + \text{PV [Expected value (Recurring Savings)]}$$

Equation 5

In Equation (5), nonrecurring costs include the expenditures for display and data transmission hardware/equipment. These cash flows occur at installation and are by definition present values. Recurring costs include annual costs for weather data/transmission and maintenance for the purchased equipment. The annual cost of equipment maintenance was estimated at 10% of the non-recurring investment. Recurring savings include annual diversion avoidance and savings in reduced flight time

Sensitivity of the business case to changes in the saving and cost terms was evaluated in two ways. The first approach developed a decision reversal table for each market segment. These tables showed the percentage of change in a cost or savings term that is required to reverse the business case from positive to negative or vice versa. Decision reversal tables are categorized as a

“one at a time” method since only one factor varies at a time.

The second sensitivity approach used Monte Carlo simulation to evaluate combinations of changes in all elements in Equation (5). The following sections describe these two sensitivity approaches for the five market segments and begin with review of the base business case.

BASE BUSINESS CASE CALCULATION

The base business case for cockpit weather systems used the expected values of the survey responses in Tables 1 through Table 6, with Equation (5) to calculate a net present value (NPV) and an IRR for each market segment. These calculations assumed a five-year project life and a 12% rate of return for the commercially driven market segments: transport, commuter, business, and rotorcraft. The general aviation market calculations employ a 7% rate of return since this market has more of a consumer return orientation.

Table 7 summarizes the results of the financial calculations and shows the business case for cockpit weather systems was positive in all market segments but general aviation. The payback period, defined as investment cost divided by non discounted annual cash flow, was less than three years for all segments but general aviation. For the transport and commuter segments the payback period was less than one year.

Table 7 Summary of Base Business Case Results

Market	Expected Non Recurring Cost	Net Expected Recurring Annual Cash Flow	NPV	Non Discounted Payback Period (years)	IRR
Transport	-67412	112448	337024	0.60	165%
Commuter	-29037	38501	109750	0.75	131%
General Aviation	-5892	753	-3178	NA	-13%
Business	-33452	30268	75655	1.11	86%
Rotorcraft	-7623	2736	2241	2.79	23%

The following sections examine decision reversal tables related to this base case. For each market segment, the cost or savings elements are examined one at a time to determine the amount of change required to reverse the base business case.

Sensitivity to Changes in Survey Data – Transport Segment

This section develops a decision reversal table to examine the sensitivity of the transport market business case to changes in one of the survey factors at a time. Table 8 shows that, with other factors held constant, the total investment costs (sum of display and data link equipment non recurring investment) would have to increase by over 350% (\$67,412 to over \$300,000) to change the transport market business case to a negative present value. Similarly, the savings related to diversion and flight time would have to decrease by over 100% (turn into costs) to cause a decision reversal. Table 8

demonstrates that the transport segment business case was insensitive to changes in the survey parameters.

Table 8 Decision Reversal Table - Transport Segment

Decision Reversal Table		Transport Market Segment	
Cost Description and Related Survey Question	Expected Value from Survey	Value to Reverse Decision	Percent change
11. Recurring- weather/ transmission (\$/ yr.)	5197	98500	1795%
12 + 13: Non recurring data link + display (\$)	67412	306000	354%
Savings Description			
15. Diversion Cost Avoidance (\$/ yr.)	75000	-18500	-125%
16. Minutes saved per year (min/yr.)	671	-600	-189%
17. Value per minute (\$/min.)	74	-66	-190%

Sensitivity to Changes in Survey Data – Commuter Segment

This section provides a decision reversal table that examines the sensitivity of the commuter market business case to one at a time changes in the survey factors. Similar to the transport market, Table 9 demonstrates the commuter segment business case was insensitive to changes in the survey parameters.

Table 9 Decision Reversal Table - Commuter Market Segment

Decision Reversal Table		Commuter Market Segment	
Cost Description and Related Survey Question	Expected Value from Survey	Value to Reverse Decision	Percent change
11. Recurring- weather/ transmission (\$/ yr.)	2045	34000	1562%
12 + 13: Non recurring data link + display (\$)	29037	113000	289%
Savings Description			
15. Diversion Cost Avoidance (\$/ yr.)	25000	-6900	-128%
16. Minutes saved per year (min/yr.)	568	-355	-163%
17. Value per minute (\$/min.)	33	-19.8	-161%

Sensitivity to Changes in Survey Data – General Aviation Segment

This section provides a decision reversal table to examine the sensitivity of the general aviation market business case to one at a time changes in the survey factors. Table 10 demonstrates the general aviation segment business case was sensitive to changes in the survey parameters. For example, a 32% decrease in the non recurring costs of the display system and data link produces a favorable present value for this market.

Table 10 Decision Reversal Table- General Aviation Market Segment

Decision Reversal Table		General Aviation Market Segment	
Cost Description and Related Survey Question	Expected Value from Survey	Value to Reverse Decision	Percent change
11. Recurring- weather/ transmission (\$/ yr.)	433	-205	-147%
12 + 13: Non recurring data link + display (\$)	5892	4000	-32%
Savings Description			
15. Diversion Cost Avoidance (\$/ yr.)	1000	1700	70%
16. Minutes saved per year (min/yr.)	320	565	77%
17. Value per minute (\$/min.)	2	4.76	97%

Sensitivity to Changes in Survey Data – Business Segment

This section examines the sensitivity of the business market financial case to one at a time changes in the survey factors. Table 11 demonstrates the business market financial case was insensitive to changes in the survey cost and saving factors.

Table 11 Decision Reversal Table - Business Market Segment

Decision Reversal Table		Business Market Segment	
Cost Description and Related Survey Question	Expected Value from Survey	Value to Reverse Decision	Percent change
11. Recurring- weather/ transmission (\$/ yr.)	1976	24000	1114%
12 + 13: Non recurring data link + display (\$)	33452	91000	172%
Savings Description			
15. Diversion Cost Avoidance (\$/ yr.)	17308	-4500	-126%
16. Minutes saved per year (min/yr.)	563	-85	-115%
17. Value per minute (\$/min.)	32.50	-4.75	-115%

Sensitivity to Changes in Survey Data – Rotorcraft Segment

This section provides a decision reversal table to examine the sensitivity of the Rotorcraft market business case to changes in the survey factors. Table 12 demonstrates the Rotorcraft segment business case was sensitive (on a percentage basis) to changes in every survey factor but recurring weather data/transmission cost. For example a 30% increase in non recurring investment resulted in a negative NPV. Similarly, if diversion cost avoidance decreases by 21%, the NPV of cockpit weather systems will turn negative. On an absolute basis, the reversal change in the relatively “insensitive” factor, recurring weather data and transmission cost, is not large. The 153% change involves only an \$847 increase (\$1400-\$553) in annual cost.

Table 12 Decision Reversal Table - Rotorcraft Market

Decision Reversal Table		Rotorcraft Market Segment	
Cost Description and Related Survey Question	Expected Value from Survey	Value to Reverse Decision	Percent change
11. Recurring- weather/ transmission (\$/ yr.)	553	1400	153%
12 + 13: Non recurring data link + display (\$)	7623	9900	30%
Savings Description			
15. Diversion Cost Avoidance (\$/ yr.)	2083	1640	-21%
16. Minutes saved per year (min/yr.)	360	220	-39%
17. Value per minute (\$/min.)	5.47	3.55	-35%

Monte Carlo Simulation

In reality, multiple factors in Equation (5) may simultaneously vary in a random manner. To assess the impact of combinations of changes, this section employs Monte Carlo Simulation methods to analyze the range of possible business case outcomes. To describe the variability of the survey data in terms of concurrent random variation, probability distributions were fitted to survey response data. For example, in contrast to the base business case which was developed using expected values from Equation (1), a triangular distribution may be derived from the survey data and used to provide random estimates of non recurring display costs. This distribution may be selected based

on estimates of the minimum, most likely, and maximum values using the survey responses and the mid points of the response intervals.

In addition to the possible variation of the survey data, two other important business case elements were varied in the Monte Carlo simulation: the rates of return expected by the market segments and the amount of annual maintenance cost. The base case employed a 7% rate of return for the general aviation segment and a 12% rate of return for all other segments. The simulation used uniform distributions for rates of return with rates varying from 5% to 8% for the general aviation segment and between 12% and 17% for the other segments. For recurring maintenance costs, the base case used 10% of initial investment. The simulation used a uniform distribution of recurring maintenance costs that ranged from 10% to 15% annually. For all other data, triangular distributions were employed.

Using the probability distributions discussed above to represent the impact of random variation on the business case elements for cockpit weather systems, 1000 iterations of randomly selected values for Equation (5) were simulated. Table 13 summarizes the results of that analysis.

Table 13 Results of Monte Carlo Simulation – 1000 Iterations

	Transport	Commuter	General Aviation	Business	Rotorcraft
Mean NPV \$ from 1000 Iterations	303828	98352	636	71884	-313
Standard Deviation of NPV \$ from 1000 Iterations	49378	24515	3839	23130	3730
Percent 1000 Iterations Unfavorable (Negative NPV)	0%	0%	40%	0%	50%
Lower 95% Confidence Interval for Mean Present Value	300767	96832	398	70450	-544
Upper 95% Confidence Interval for Mean Present Value	306888	99871	874	73317	-82

The first two rows in Table 13 contain the mean and standard deviation of the NPV calculation results from the 1000 simulation iterations. The mean NPV is positive for all market segments but rotorcraft. For the transport, commuter, and business sectors the mean NPVs are consistent with the previous results for the base business case in Table 7. The third row contains the percentage of the iterations in the simulation, that resulted in a negative NPV. Transport, commuter, and business had no occurrences of a negative NPV. On the other hand, the general aviation (40%) and rotorcraft (50%) segment financial cases have significant probabilities of an unsuccessful financial result.

To further benchmark the Monte Carlo produced expected return for each market segment, Equation (6) identified the 95% confidence interval for the mean NPV of the investment outcome.

$$\bar{x} \pm Z(\alpha/2) \frac{S}{\sqrt{n}} \quad \text{Equation 6}$$

In Equation (6), \bar{x} is the mean of the simulation results, $Z(\alpha/2)$ is the Z score for the $(1-\alpha)$ confidence interval, S is the standard deviation of the simulation results, and n is the sample size. The last two lines in Table 13 contain the NPV interval calculations from Equation (6) for the market segments. For example, there is a 95% confidence level that the mean NPV for the general aviation segment is favorable (between \$898 and \$374). On the other hand, there is a 95% confidence level that the mean NPV for the rotorcraft market is not favorable (between -\$82 and -\$544).

Table 13 indicates a change from prior analysis in the financial case results for the rotorcraft and general aviation segments. Table 7 showed a positive business case for rotorcraft and a negative business case for general aviation based on use of the expected values of survey responses developed using Equation (1). Table 13 reverses this outcome with general aviation favorable and rotorcraft unfavorable. The difference in these two results is based on the use of probability distributions in the Monte Carlo simulation. For example, the expected value of a triangular distribution is different from the expected value calculated using Equation (1). This result confirms the point that the business case for these two segments is sensitive to change in cost and saving factors.

BUSINESS CASE SUMMARY

The financial analysis indicated that there is a strong adoption case for the transport, commuter, and business market segments. Based on the survey data, the investment results for these market segments showed a positive present value that was insensitive to change in cost and savings parameters.

Using expected values from the survey data, the base business case analysis for general aviation was negative and was most sensitive to the cost of the display and data link hardware. Reductions in these costs could change the general aviation case from marginal to positive. The Monte Carlo simulation demonstrated this point by producing a positive estimate for the business case using random probability distributions.

The rotorcraft market base business case was positive but it was sensitive to a number of factors including the cost of the investment for display and data link hardware, cost avoidance and saving parameters. The Monte Carlo simulation verified this sensitivity by identifying a negative NPV. The short flight durations and limited savings in diversion costs reduce the positive cash flow potential for this market segment.

However, the importance of a strong business case for these two market segments is unclear since the survey data indicated that safety rather than cost saving would be the primary reason to adopt advanced cockpit weather information systems.

MARKET SEGMENT ADOPTION RATE ESTIMATES

Market penetration of new technologies is typically described by the S shaped or logistic curve shown in Figure 12. The survey asked participants to estimate four values for the adoption curves that describe market penetration of cockpit weather information systems for each market segment: (A) years from the present to achieve 10% of the maximum, (B) years from the present to achieve 50% of the maximum, (C) years from the present to achieve 90% of the maximum, and (D) maximum market penetration. Two approaches were employed to analyze these responses to develop estimates of market penetration rates: response averages/confidence intervals and the Fisher and Pry model [3]. The following sections discuss these results.

ADOPTION RATE ESTIMATE USING RESPONSE MEAN AND CONFIDENCE INTERVALS

The first approach to estimate the market penetration of cockpit weather systems used the response mean and related confidence intervals for the four values (maximum penetration and years to 10%, 50%, and 90% of the maximum) that were identified in the survey responses. Equation (7) defines the $(1-\alpha)$ confidence interval for a population mean.

$$\bar{x} \pm t(\alpha/2, n-1) \frac{S}{\sqrt{n}} \quad \text{Equation 7}$$

In Equation 7, \bar{x} is the average survey response, $t(\alpha/2, n-1)$ is the student t distribution value with $(n-1)$ degrees of freedom and a $(1-\alpha/2)$ confidence level, S is the standard deviation of the survey responses, and n is the sample size.

The results of these calculations are summarized in Table 14 for the five market segments.

Table 14 Summary of Mean and Confidence Interval for Market Penetration Data

Market		Maximum Penetration (%)	Years Until 10% of Maximum	Years Until 50% of Maximum	Years Until 90% of Maximum
Transport	Upper 90% Estimate	86	5.0	10.3	18.9
	Sample Mean	79	4.0	9.1	16.4
	Lower 90 % Estimate	72	3.0	7.8	14.0
Commuter	Upper 90% Estimate	79	6.0	12.1	17.7
	Sample Mean	73	4.6	10.1	15.4
	Lower 90 % Estimate	66	3.2	8.1	13.0
General Aviation	Upper 90% Estimate	62	5.4	11.9	16.9
	Sample Mean	54	4.5	10.3	15.0
	Lower 90 % Estimate	45	3.5	8.7	13.1
Business	Upper 90% Estimate	85	4.8	9.4	14.5
	Sample Mean	80	3.7	7.9	12.7
	Lower 90 % Estimate	74	2.7	6.3	10.8
Rotorcraft	Upper 90% Estimate	51	6.8	12.8	17.8
	Sample Mean	40	4.9	10.5	15.6
	Lower 90 % Estimate	29	3.0	8.3	13.4

FISHER – PRY APPROACH TO ADOPTION RATE ESTIMATES

The previous approach develops point estimates for market penetration but does not provide continuous shapes for the possible adoption curves. Fisher and Pry [3] used the mathematical expression for the S-shaped logistic curve described in Equation (8) as a basis for estimating market penetration curves.

$$f = \frac{1}{1 + e^{-b(t-t_0)}} \quad \text{Equation 8}$$

For Equation (8), f is the fraction of the market that has adopted the new product; b is a technological constant typically interpreted as the initial rate of adoption [4]; t_0 is the time for the product to penetrate half of the market; t is the time since product introduction. Equation (8) can be rewritten as Equation (9).

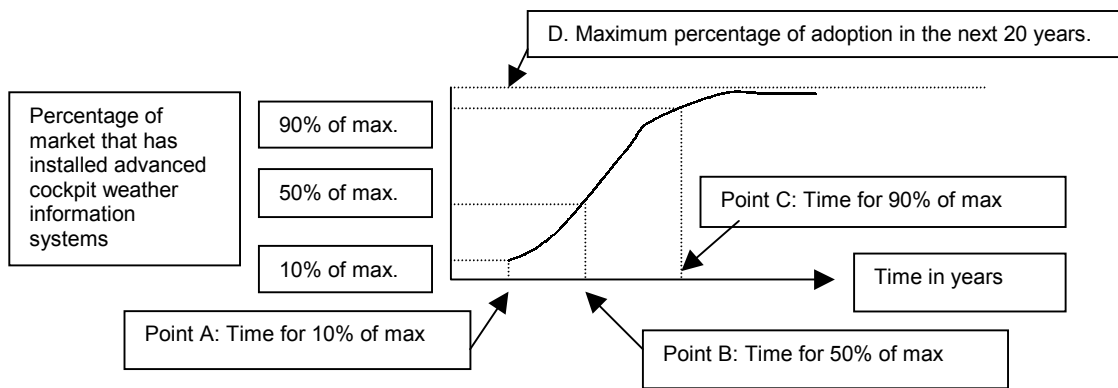


Figure 12 Market Penetration Curve and Survey Data

$$\frac{f}{(1-f)} = e^{b(t-t_0)} \quad \text{Equation 9}$$

When market penetration is limited to less than 100%, Equation (9) may be rewritten as Equation (10) where L is the upper limit in market share and bt_0 is restated as a constant term with a positive sign, c [5].

$$\frac{f}{(L-f)} = e^{b(t-t_0)} = e^{bt+c} \quad \text{Equation 10}$$

Equation (10) can be rewritten in a log-linear form as Equation (11).

$$\ln\left(\frac{f}{L-f}\right) = bt + c \quad \text{Equation 11}$$

Survey participants provided estimates for the maximum penetration, L, and the market penetration, f, at three points in time. Using this survey data and the logarithmic form of the Fisher-Pry model described by Equation (11), least squares linear regression can be applied to develop estimates for the constants b and c in Equation (11). These estimates are presented in Table 15.

The coefficient of determination (R^2) is a common measure of the goodness of fit of a regression model since it describes the percentage of data variation that the regression equation explains. For each market segment, Table 15 shows the regression model provides a reasonable fit since it explained over 60% of the variation in the survey data.

Table 15 Linear Regression Results for Fisher-Pry Model

	Transport	Commuter	General Aviation	Business	Rotorcraft
Regression term - c	-2.592	-2.562	-2.751	-2.457	-2.402
Regression Term - b	0.267	0.252	0.265	0.298	0.237
R squared- % explained variation	0.744	0.674	0.688	0.666	0.610

Using the estimates for b and c and Equation (11), values for $(f/(L-f))$ can be developed for each year (t) in the future. Since an estimate for L was obtained from the survey data (Maximum penetration column in Table 14), the percentage of the maximum penetration, f, in the term $(f/(L-f))$, can be calculated. The results of these calculations for the market segments are shown in Figure 13. The estimated adoption rates described in Table 14 and Figure 13 are consistent.

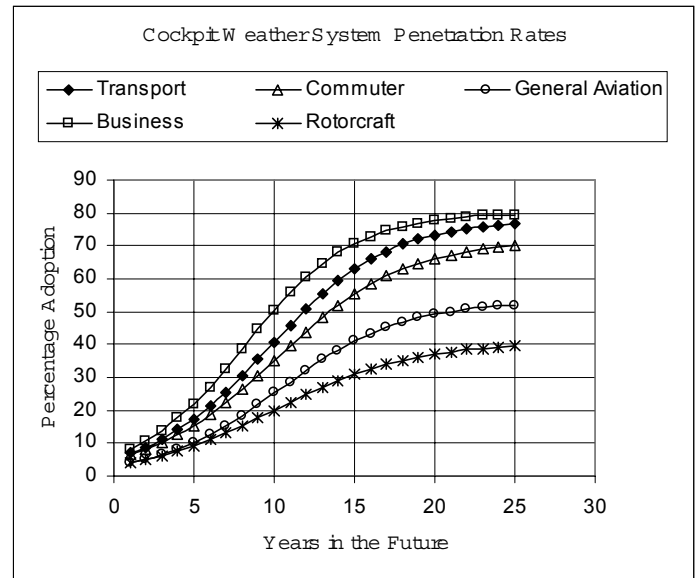


Figure 13 Cockpit Weather System Penetration Estimates

OVERVIEW OF OPEN ENDED SURVEY COMMENTS

The survey solicited general comments from participants. Although the comments were wide – ranging and varied, participants consistently highlighted several themes. These general themes are summarized in the following paragraphs without comment or interpretation. The complete set of comments is available from the authors.

- **System Integration:** Although the business case for cockpit weather information systems was strong and the required product characteristics were consistently understood, participants expressed the concern that the challenge of integrating the necessary elements to develop a complete system will hinder the rate of product adoption. This system integration concern involved two levels. At the highest level, the issue was development of the cockpit weather system as an integrated product that can be presented to customers with minimal unknowns and risk. The second level of system integration involved the flexible application of the integrated weather system product to a broad range of aircraft and cockpit hardware so the customer base can be as broad as possible.
- **System Standards:** Participant comments identified areas in which a lack of standards may slow market adoption of cockpit systems. These concerns appear to focus on two interrelated areas: data transmission/link standards and weather information presentation standards.
- **Cost of Supporting Ground Operations:** Several participants identified a potential barrier as the unknown costs associated with maintaining the ground infrastructure for collecting and disseminating weather data for cockpit weather systems.
- **Cost Justification:** Many survey participants believed that a major barrier to market adoption will be the

cost justification process required in a corporate context to obtain the funds required to implement cockpit weather systems.

CONCLUSIONS AND RECOMMENDATIONS

The survey results indicated that cockpit weather systems are a viable product concept with characteristics that are consistent across market segments. Based on estimates for system investment costs, and recurring costs/savings, the business case for these systems was very strong in the transport, commuter, and business markets. Together, these two factors should provide momentum for development of viable products and marketplace adoption.

The business cases for the rotorcraft and general aviation markets were sensitive to variation in costs and savings. However, survey responses indicated that safety is the primary motivation for these segments to adopt cockpit weather systems.

Two approaches were employed to estimate market adoption rates using the estimates from survey participants. These methods provided consistent estimates for the time periods within which adoption will occur. In general, cockpit weather systems will achieve their maximum market penetration levels within the next 25 years and will achieve 50% of these levels within the next 8-11 years. For all market segments, cockpit weather systems will play a role in achieving the national goals for aviation safety.

This survey has highlighted several areas for future research in addition to evaluating the issues identified in the previous section of participant comments.

- It is critical to investigate the business case model in more detail. Information is needed from aircraft owners and operators to substantiate the relationship between cockpit weather systems and the ability to make decisions that reduce costs associated with diversions and flight time.
- Safety is a significant factor in the adoption decision for all market segments. It would be useful to understand how much adopters are willing to pay for safety and how adopters measure incremental levels of safety.

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